# Delineation of potential sites for rainwater harvesting structures using a geographic information system-based decision support system

Shereif H. Mahmoud, F. S. Mohammad and A. A. Alazba

## ABSTRACT

This paper presents a methodology based on a decision support system (DSS) that employs remote sensing and field survey data and geographic information system (GIS) to identify potential rainwater harvesting areas (RWH). This DSS was implemented to obtain suitability maps and to evaluate the existing RWH structures in the study area. The DSS inputs comprised maps of rainfall surplus, slope, potential runoff coefficient, land cover/use, and soil texture. On the basis of an analytical hierarchy process analysis taking into account five layers, the spatial extents of RWH suitability areas were identified by multi-factor evaluation. The spatial distribution of the classes in the suitability map showed that the excellent and good areas are mainly located in the southern and western parts of the study area. On average, 12.2% and 22.2% of the study area are classified as excellent and good for RWH, respectively, while 34.7% and 30.9% of the area are classified as moderately suitable and poorly suited and unsuitable, respectively. Most of the existing RWH structures that are categorized as successful were within the good (72% of the structures) areas followed by moderately suitable (24% of the structures) and excellent areas (4% of the structures).

**Key words** | analytical hierarchy process, decision support system (DSS), GIS, multi-factor evaluation (MFE), rainwater harvesting

**Shereif H. Mahmoud** (corresponding author)
Alamoudi Water Research Chair,
King Saud University,
Riyadh,
Saudi Arabia
E-mail: *eng.shereif1@hotmail.com*

**F. S. Mohammad**
Department of Agricultural Engineering,
College of Food and Agriculture Science,
King Saud University,
Riyadh,
Saudi Arabia

**A. A. Alazba**
Alamoudi Water Research Chair,
King Saud University,
Riyadh,
Saudi Arabia

## INTRODUCTION

The Kingdom of Saudi Arabia is one of the hottest and driest subtropical desert countries in the world (Mahmoud 2014a). With an average of 112 mm of precipitation per annum, much of the Kingdom falls within the standard definition of a desert. Saudi Arabia receives an estimated 158.47 billion $m^3$ of rainwater annually (Al-Rashed *et al.* 2000; Mahmoud 2014a). The total surface runoff generated from rainfall is estimated as 3.21 billion $m^3 yr^{-1}$ (Khouri *et al.* 1990), and this problem is compounded by the lack of rainwater harvesting (RWH) practices in the country. The exploitation of subsurface water from deep aquifers also depletes resources that have taken decades or centuries to accumulate and on which the current annual rainfall has no immediate effect. Water limitations are particularly severe in the Kingdom of Saudi Arabia where agriculture is almost completely dependent on groundwater, which is difficult and expensive to obtain. Water for agriculture as well as domestic purposes has to be obtained by desalination, which is a cost-intensive process. Owing to such limitations in water resources and the potential increase in the area under cultivation, it is necessary to develop an alternative supplementary water source.

RWH may help build up water supplies and achieve a sustainable development of water resources in the region. Against the background of climate change and water shortage in the Kingdom, RWH assumes importance in meeting the great need for new water supplies. RWH is now adopted in many urban areas for increasing the ground recharge as well as for other purposes, such as achieving sustainable development. RWH is being promoted in the Kingdom by

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the Ministry of Water and Electricity (MOWE) to avoid severe drought conditions.

In the past, different forms of RWH have been practiced by creating diversions in which the spate flow from normally dry watercourses ('Wadi' flow) is transported into agricultural lands in the Middle East. Among other examples of places where RWH has been adopted are the Negev desert (Evenari *et al.* 1971) and the desert areas of Arizona and northwest Mexico (Zaunderer & Hutchinson 1988) and southern Tunisia (Pacey & Cullis 1986). The importance of traditional, small-scale systems of RWH in sub-Saharan Africa (Reij *et al.* 1992) and to buildings in urban areas (Gould & Nissen-Petersen 1999) has been identified. Several RWH systems are currently in use for a wide variety of applications (Fewkes 1999; Gould & Nissen-Petersen 1999). Numerous benefits of RWH have been reported (Jackson *et al.* 2001; Krishna 2003), underlining the choice of RWH as a water resource management solution against the background of climate change. Studies on ecological and hydrological interactions may determine the resource use and its influence on the vegetation composition and diversity (Ludwig *et al.* 2005; Yu *et al.* 2008).

Identification of potential sites for RWH (PRWH) is an important step toward maximizing water availability and land productivity in semi-arid areas (Mbilinyi *et al.* 2007; Mahmoud *et al.* 2014a). Potential areas for RWH are selected on the basis of several factors, including the biophysical and socioeconomic conditions of the target region. FAO (2003), as cited by Kahinda *et al.* (2008), listed the key factors to be considered when identifying RWH sites: climate (rainfall), hydrology (rainfall–runoff relationship), topography (slope), agronomy (land use/cover), soil (texture), and socioeconomic factors. Pacey & Cullis (1986) emphasized the importance of social, economic, and environmental conditions when planning and implementing RWH projects.

In recent times, an integrated study of runoff modeling by employing remote sensing (RS) and geographic information systems (GIS) technologies has gained importance in determining suitable sites for water recharging/harvesting structures (Padmavathy *et al.* 1993; El-Awar *et al.* 2000; Ravishankar & Mohan 2005; De Winnaar *et al.* 2007; Mahmoud 2014b). Although RWH has been extensively researched, only few studies have applied such technologies for arid regions. Examples of such works include the study conducted by Gupta *et al.* (1997) who developed a GIS-based water harvesting strategy for the semi-arid area of Rajasthan, India; the topography and soil information was digitized to form the GIS database, and land cover information was derived in the form of the normalized difference vegetation index from the satellite data of IRS-1A. Six basins were delineated using a digital elevation model (DEM), and the total acreage in different slope classes was estimated. These maps were input to derive a modified Soil Conservation Service (SCS) runoff curve number. The results demonstrated the feasibility of applying GIS technologies for water harvesting planning over larger semi-arid areas. Durga Rao & Bhaumik (2003) considered land use, soil, slope, runoff potential, proximity, geology, and drainage as factors to identify suitable sites for RWH. Mbilinyi *et al.* (2007) presented a GIS-based decision support system (DSS) that employs RS techniques and limited field survey to identify PRWH. Bothale *et al.* (2008) presented a DSS WARIS as a case study for identifying suitable sites for water harvesting structures in the upper Betwa watershed of Betwa Basin, India. Ramakrishnan *et al.* (2008) used slope, fracture pattern, porosity, permeability, runoff potential, stream order, and catchment area as the factors for selecting suitable sites for various RWH/recharging structures in the Kali watershed in Dahod district, Gujarat, India, using RS and GIS techniques. Similarly, Singh *et al.* (2009) used the satellite imagery of Soankhad watershed (IRS-1C, P6) and the corresponding land use map, soil map, and slope map and implemented DEM hydro processing in their case study of Soankhad watershed in the Punjab, India.

Multi-factors decision-making (MFDM) plays a critical role in many real life problems (Mahmoud & Alazba 2014b). It requires the evaluation of a set of alternatives in terms of a set of decision factors that are often in conflict with each other; further, the collection of the required data is generally cost-intensive (Triantaphyllou & Mann 1995). According to Malczewski (2004), the data acquisition, storage, retrieval, manipulation, and analysis capabilities of the GIS and the MFDM's capabilities for combining the geographical data analysis and the decision-maker's preferences into uni-dimensional values of alternative decisions are of critical importance in decision-making. Analytic Hierarchy

Process (AHP) is a GIS-based MFDM that combines and transforms spatial data, i.e., the input into result decision, i.e., the output (Saaty 1977, 1994). The procedures include the utilization of geographical data and the decision-maker's preferences and manipulating them according to specified decision rules referred to as factors and constraints. Saaty (1990) reported that in an AHP, the selected factors are structured in a hierarchy starting from the overall aim to factors, sub-factors, and alternatives in successive levels. Jabr & El-Awar (2005) presented a methodology for determining suitable sites for water harvesting reservoirs in a 300-km$^2$ area in Lebanon to improve the agriculture potential in this region characterized by low and erratic precipitation. They employed a three-step Hydro Spatial AHP: (1) the required spatial coverage was obtained using ArcGIS software; (2) the runoff in the watersheds was simulated using Watershed Modeling System; (3) a decision hierarchical structure was developed and implemented to rank various potential reservoir sites depending on their suitability as expressed in terms of a Reservoir Suitability Index. Saaty (2008) outlined four steps for implementing an AHP: (1) define the issue to be considered; (2) identify the goal, which is the factors upon which the other elements will depend and which should be at the top of the decision-making tree; (3) develop a pair-wise comparison matrix; (4) weight priorities for each element with priorities obtained in the comparison matrix to obtain the priority that will form the basis of decision-making for alternatives at the bottom of the hierarchy.

The object of the study is to develop a methodology based on a DSS that employs RS and field survey data and GIS to identify suitable RWH areas in Al-Baha region, Saudi Arabia.

## STUDY AREA AND DATA

The present study is a multidisciplinary study involving a field survey and modeling. A variety of techniques, such as GIS, RS, and aerial image interpretation were employed in this study. Al-Baha Province, which lies in the western part of the Kingdom of Saudi Arabia, was selected as the study area (Figure 1). Information on past and recent RWH structures in Al-Baha was obtained through a literature review, a Global Positioning System (GPS) field survey, and from the responses of farmers obtained during interviews using a semi-structured questionnaire.

### Study area

Al-Baha Province (41°–42° N, 19°–20°E) was selected as the target region because of the considerable divergence in its topography and climate. Its climate, in general, is arid. Relative humidity varies between 52 and 67%, and temperatures range between 12 °C and 23 °C. Rainfall ranges between 200 and 600 mm/year and is much higher than the national average. The province is situated in Hejaz, between the holy Makah and Asser, and is the smallest of the Kingdom's provinces with an area of 12,000 km$^2$.

## METHODOLOGY

The identification of suitable areas for RWH is a multi-objective and multi-factors problem. The major steps in mapping in this study were as follows:

- Selection of factors.
- Assessment of the suitability levels of the factors for RWH.
- Assignment of weights to these factors.
- Collection of spatial data for the factors through various sources, including a GPS survey, to supplement and generate maps using GIS tools.
- Development of a GIS-based suitability model, which combines maps through a spatial multi-factors evaluation (SMFE) process.
- Generation of suitability maps.

We selected the following five factors for identifying PRWH:

- Soil map.
- Land cover and land use (derived from available RS data).
- Slope (i.e., topography).
- Runoff coefficient.
- Rainfall surplus precipitation.

The factors and their application for mapping the RWH potential in the region are presented in Figures 2

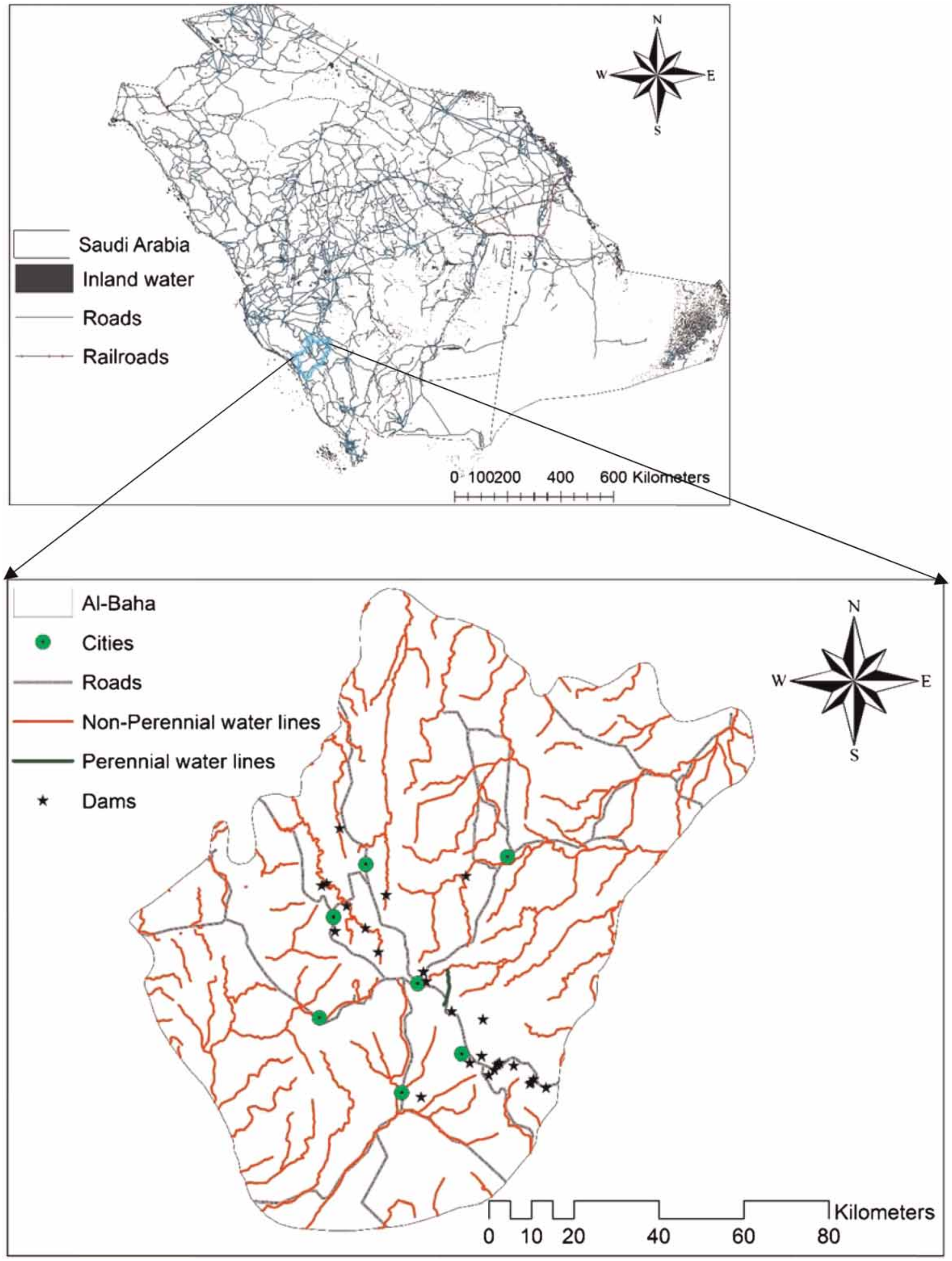

**Figure 1** | A location map of the study area.

and 3. Because of the different scales on which the factors were measured, the values contained in the factor maps have to be converted into comparable units for SMFE. Therefore, the factor maps were re-classed into four comparable units or suitability classes, namely: 5 (excellent), 4 (good), 3 (moderate), 2 and 1 (poor and unsuitable). The suitability classes were then used as the basis to generate the factors map.

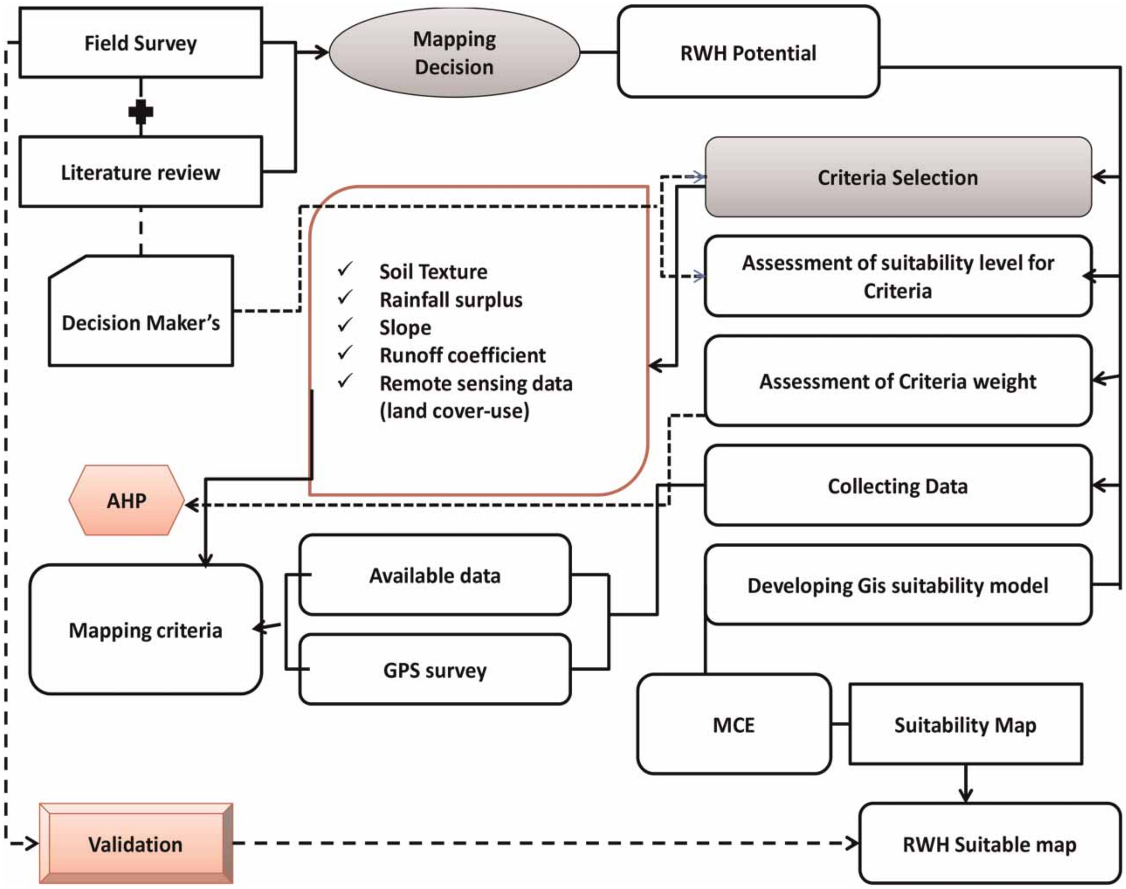

**Figure 2** | The work flow chart.

## DATA AND PROCESSING

### Soil map

A soil map was developed for the study area under the guidance of soil experts by using GPS data to identify the soil texture in the region. GPS points for soil texture for all the area covered during the field survey were imported into ArcGIS to develop the soil texture map (Figure 4). Three soil classes – loam, clay, and silty clay – have been identified in the study region. Loamy soil covers 85.8% of the study area (Table 1); this soil type has a moderate infiltration rate when it is thoroughly wetted, and is classified moderately to well-drained soils with moderately fine to moderately coarse textures.

Soils are classified by USDA-SCS (1988) into four hydrologic soil groups based on the soil's runoff potential. The four hydrologic soil groups are A, B, C, and D, where group A generally has the smallest runoff potential and D the greatest. The soil in the study area is mainly classified into classes B and D. These groups were used to develop the potential runoff coefficient (PRC) for the study area.

### Land cover and land use (derived from available RS data)

Landsat 5/7 TM/ETM images were obtained for the year 2000 from the King Abdul-Aziz City for Science and Technology (KACST). These images were incorporated with collected GPS field survey data, and ultimately utilized for categorizing land use and land cover (LULC). ERDAS Imagine 2013 software was used to mosaic the collected satellite images. The Iso Cluster unsupervised classification tool and maximum likelihood classification

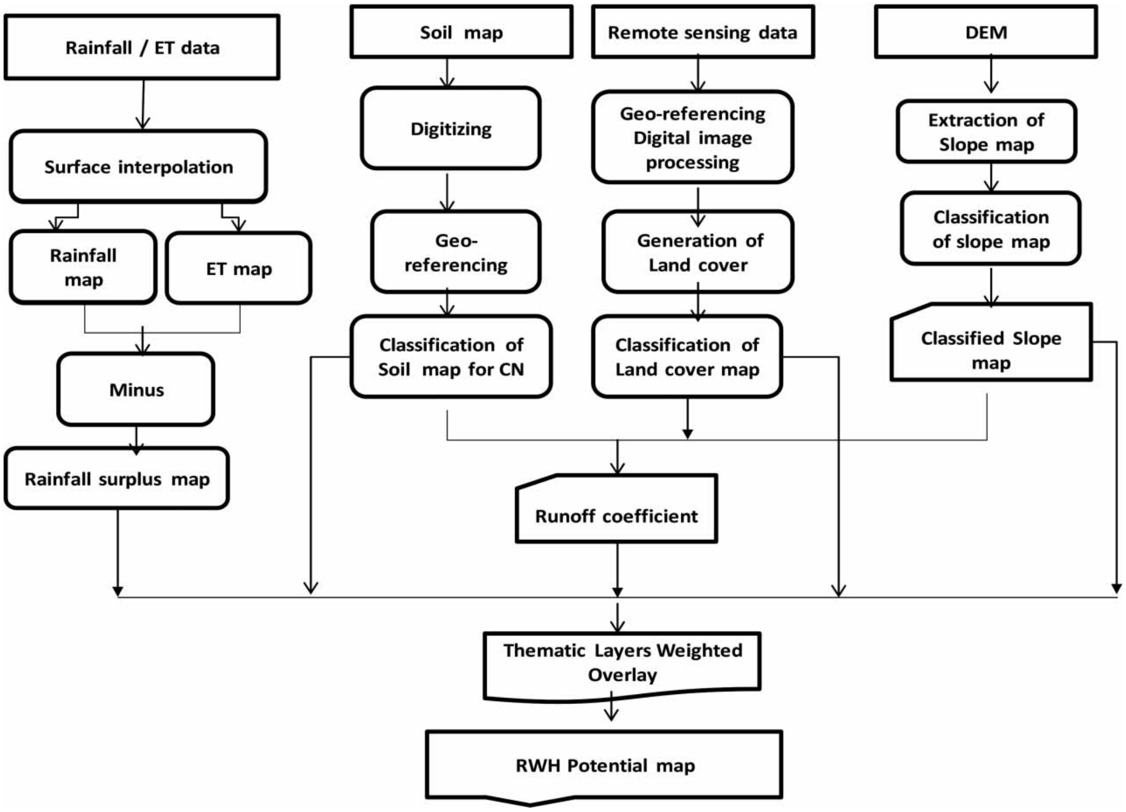

**Figure 3** | A conceptual framework of RWH potential mapping.

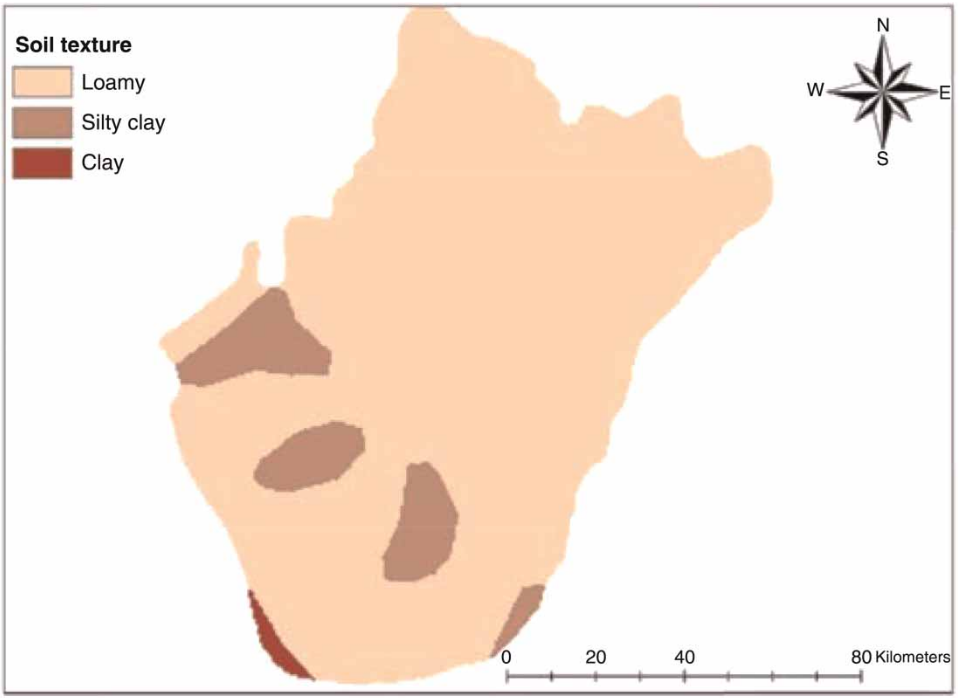

**Figure 4** | A soil texture map of the study area. Note: Typical input maps, used for the development, testing and validation of DSS.

**Table 1** | Areas covered by different soil classes in the study region

| Soil texture | Area (km$^2$) | % of total area |
|---|---|---|
| Loamy | 10,476.9 | 85.8 |
| Silty clay | 1,028.8 | 8.4 |
| Clay | 701.4 | 5.7 |
| Total | 12,207.1 | 100.0 |

function in the ArcGIS Spatial Analyst were used for the unsupervised classification. Training samples collected during field survey were used to create spectral signatures (i.e., reflectance values) for the supervised classification to identify what the cluster represents (e.g., water, bare earth, and dry soil). The LULC map shows four main classes, namely, cropland, sparsely vegetated land, forest and shrub land, and bare soil (Figure 5). The areal extent of each class is presented in Table 2.

## Slope

A DEM with 30-m resolution developed at the KACST was used to generate the slope map for Al-Baha. Sinks and flat areas were removed to maintain the continuity of flow of water to the catchment outlets (Figure 6). Slope maps (Figures 6 and 7) were generated for the study area on the basis of Al-Baha Filled DEM for identifying potential RWH sites and for determining the PRC.

## Potential runoff coefficient

The curve number is a hydrological parameter used to describe the stormwater runoff potential for drainage areas, and is a function of land use, soil type, and soil moisture (Mahmoud *et al.* 2014c). Mahmoud *et al.* (2014c) estimated the PRC using GIS based on the area's hydrologic soil group, land use, and slope for the Al-Baha region in Saudi Arabia. Mahmoud *et al.* (2014c) noted that in the absence of reliable ground measurements of rainfall, a product can satisfactorily be applied to estimate the spatial rainfall distribution based on the obtained values of $R$ and $R^2$ (0.9998). The PRCs generated in this study ranged from 0 to 82% of the total rainfall, as presented in Figure 8.

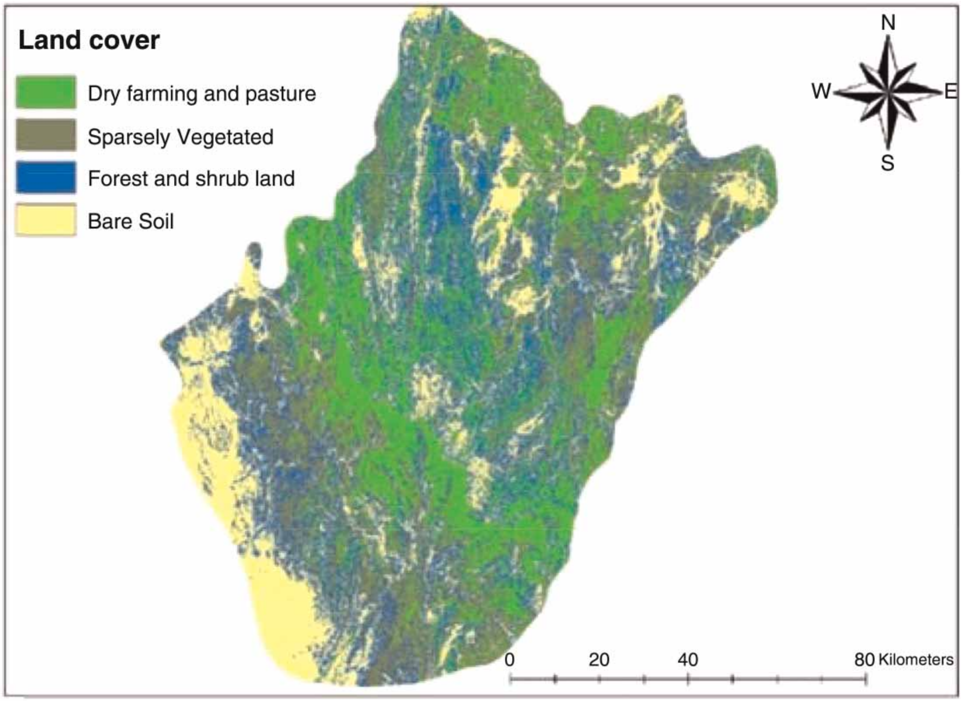

**Figure 5** | An LULC map for the study region. Note: Typical input maps, used for the development, testing and validation of DSS.

**Table 2** | Areas covered by the different land cover and land use

| Land cover/land use | Area (km$^2$) | % of total area |
|---|---|---|
| Dry land cropland and pasture | 2,870.7 | 23.5 |
| Sparsely vegetated | 2,769.3 | 22.7 |
| Forest and shrub land | 3,703.2 | 30.3 |
| Bare soil | 2,863.9 | 23.5 |
| Total | 12,207.1 | 100.0 |

### Rainfall surplus

Since the climatic data obtained from the meteorological department, Ministry of Agriculture (MOA) and MOWE were insufficient for this study, we interpolated data by using the following sources:

1. Satellite images for monthly global precipitation from (1979 to 2009) obtained from the World Data Center for Meteorology.
2. NASA Tropical Rainfall Measuring Mission (TRMM) Monthly Global Precipitation data from 1998 to 2010 obtained from NASA GES Distributed Active Archive Center.

The rainfall surplus (P-ET) map was generated by subtracting long-term average monthly evapotranspiration values of the precipitation for all meteorological stations for the period from 1950 to 2012. The annual rainfall surplus was calculated at each meteorological station by adding only the positive values of the difference (P-ET), and a map of the spatial distribution of rainfall surplus (Figure 9) generated by interpolating previous data values using ArcGIS.

## MAIN PROCESSING

### Assessment of suitability level of factors for RWH

Areas with large rainfall surplus have a high suitability rank since the surplus ensures the availability of runoff for RWH. RWH is generally more suitable for flat areas with a low slope; however, note that a slight slope is needed for better capturing the runoff. Therefore, areas with slopes of 2 to 8% have a high suitability rank. Runoff index when runoff coefficient (RC) > 0.5 is indicative of a potential area for RWH. A detailed analysis of the suitability rankings is

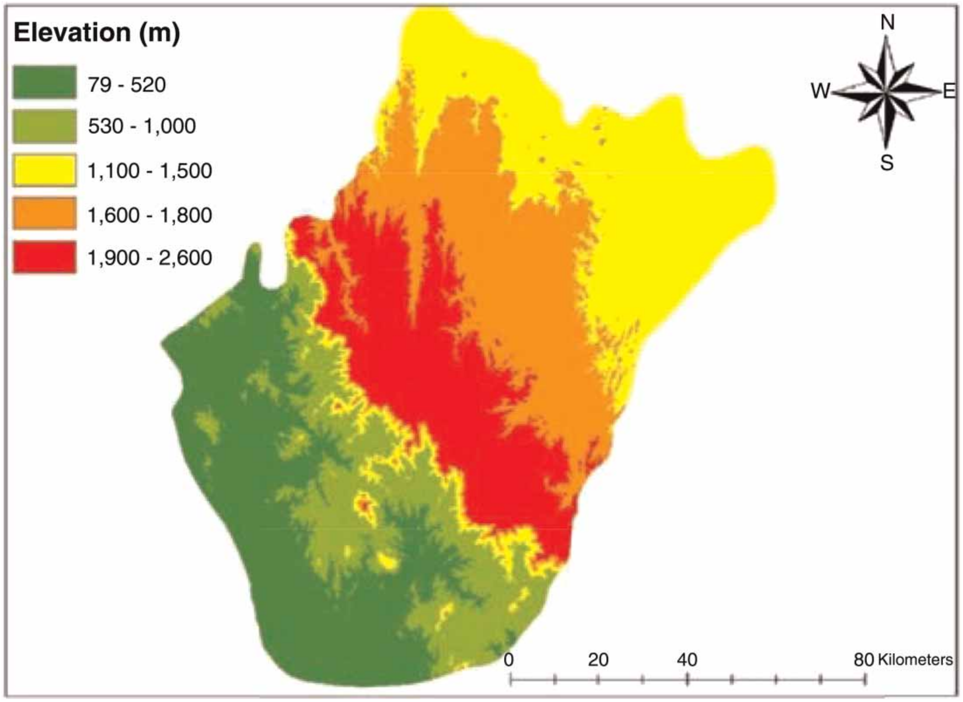

**Figure 6** | The DEM considered in the study. Note: Typical input maps, used for the development, testing and validation of DSS.

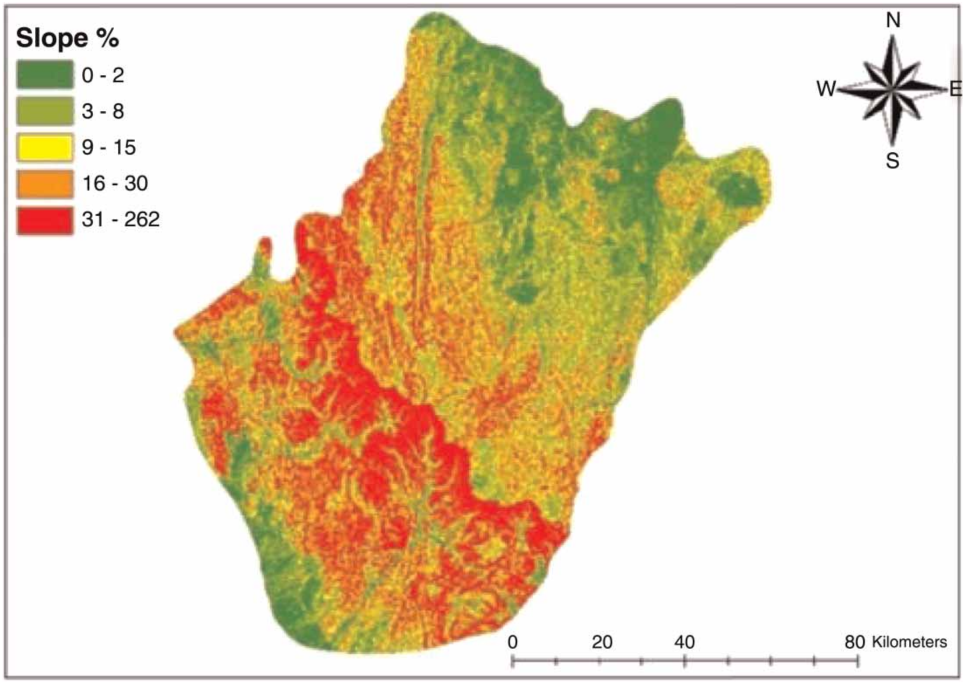

**Figure 7** | A slope map for identifying potential RWH sites. Note: Typical input maps, used for the development, testing and validation of DSS.

given by Mbilinyi *et al.* (2005). The values for each suitability category were scaled from 1 to 9 and are based on the factors proposed by Diamond & Parteno (2004). The method has been found to be robust and reliable (Diamond & Parteno 2004). The suitability rankings for soil texture, rainfall surplus, slope, land cover, and RC are shown in Table 3.

## Assignment of weights to different factors

The factors were assigned weights by applying the pair-wise ranking and rank sum methods. The final weight calculation requires the computation of the principal eigenvector of the pair-wise comparison matrix to produce a best-fit set of weights. The WEIGHT module of IDRISI software is used for this calculation. The weighting procedure is based on AHP. AHP is a MFDM method that helps the decision-maker facing a complex problem with multiple conflicting and subjective factors (e.g., location or investment selection, projects ranking, and so forth). The pair-wise comparison approach is used in IDRISI as a method for assessing weights to evaluation criteria (factor maps) in GIS-based decision-making. This method has been tested theoretically and empirically for a variety of decisions situations, including spatial decision-making.

Several papers have compiled the AHP success stories in very different fields (Zahedi 1986; Vargas 1990; Forman & Gass 2001; Kumar & Vaidya 2006; Hossain *et al.* 2007; Wang *et al.* 2009; Young *et al.* 2010; Garfì *et al.* 2011; Anane *et al.* 2012; Krois & Schulte 2014).

First, the relative importance of pair-wise combinations of the factors involved is judged using the following nine-point rating scale:

| 1/9 | 1/7 | 1/5 | 1/3 | 1 | 3 | 5 | 7 | 9 |
|---|---|---|---|---|---|---|---|---|
| Extremely | Very strongly | Strongly | Moderately | Equally | Moderately | Strongly | Very strongly | Extremely |
| Less important | | | | | More Important | | | |

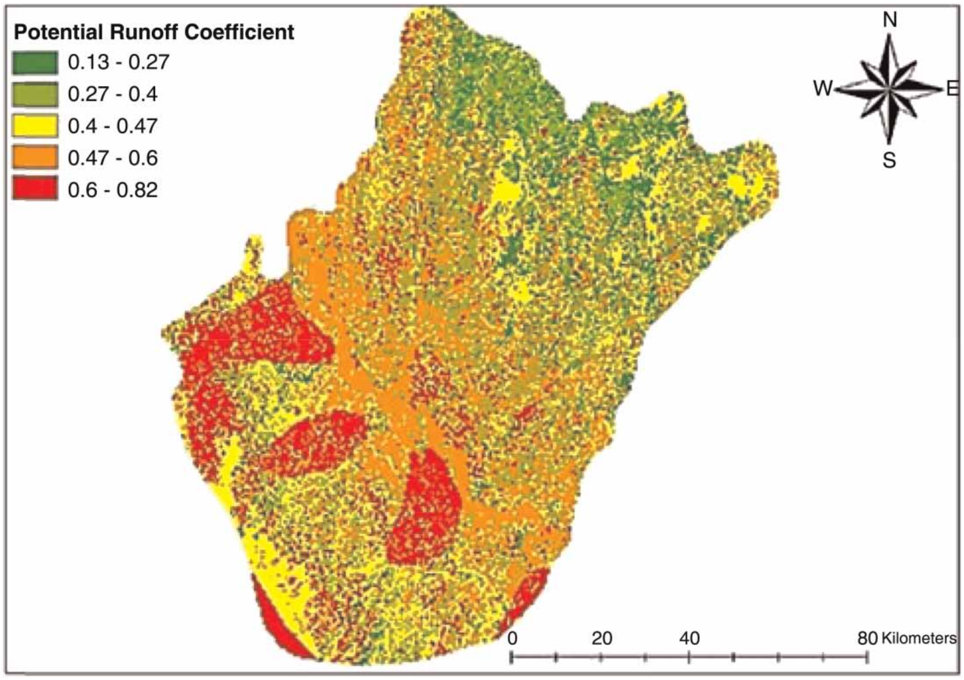

**Figure 8** | Distribution of PRCs. Note: Typical input maps, used for the development, testing and validation of DSS.

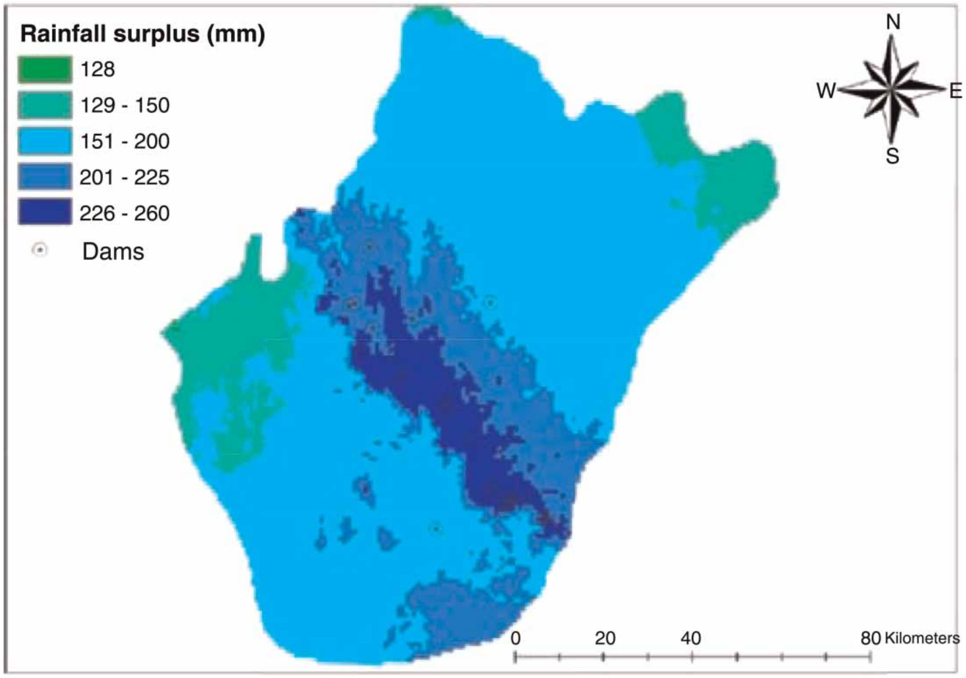

**Figure 9** | The rainfall surplus map of the study area. *Note:* Typical input maps, used for the development, testing and validation of DSS.

**Table 3** | Suitability levels for different factors for identifying PRWH

| Suitability values | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| Soil texture | Fine | Fine and medium | Medium | Medium and coarse | Coarse |
| Rainfall surplus | Large surplus | Small surplus | Medium deficit | Large deficit | Very large deficit |
| Slope (%) | 2–8 | 8–15 | 0–2 | 15–30 | > 30 |
| Land cover | Intensively cultivated | Moderately cultivated | Forest, exposed surface | Mountain | Water body, urban areas |
| Runoff index | 0.7–0.82 | 0.6–0.7 | 0.4–0.6 | 0.27–0.4 | 0–0.27 |

The expected value method calculates the weight, $W_k$ for factor $k$ according to Equation (1) (Janssen & Van Herwijnen 1994). This method takes uncertainty into account by considering the probability of each possible outcome and using this information to calculate an expected value

$$W_k = \sum_{i=1}^{n+1-k} \frac{1}{n(n+1-i)} \tag{1}$$

Here, $n =$ the number of factors, and $k =$ factor.

The accuracy of pair-wise comparison is assessed by calculating the consistency index. This index determines the inconsistencies in the pair-wise judgments and is a measure of departure from consistency based on the comparison matrices

$$CI = (\lambda - n)/(n-1) \tag{2}$$

where $\lambda$ is the average value of consistency vector, and n is the number of columns in the matrix (Saaty 1990; Vahidnia *et al*. 2008; Garfì *et al*. 2009). The consistency ratio ($CR$) is then calculated as follows:

$$CR = CI/RI \tag{3}$$

where the random index ($RI$) is an index that depends on the number of elements that are being compared (Garfì *et al*. 2009). A detailed analysis table of the RIs of matrices of order 1–15 is given by Saaty (1980).

The pair-wise rating procedure has several advantages. First, the ratings are independent of any specific measurement scale. Second, the procedure, by its very nature, encourages discussion, leading to a consensus on the weights to be used. In addition, the factors that were omitted from initial deliberations are quickly uncovered through the discussions that accompany this procedure. Experience has shown, however, that while it is not difficult to come up with a set of ratings by this means, the ratings are not always consistent. Thus, the technique of developing weights from these ratings also needs to be sensitive to these problems of inconsistency and error. To provide a systematic procedure for comparison, a pair-wise comparison matrix was created by setting out one row and one column for each factor in the problem (Table 4). The rating is then done for each cell in the matrix. Since the matrix is symmetrical, ratings are provided for one half of the matrix and then inferred for the other half.

The CR of the matrix, which shows the degree of consistency achieved when comparing the factors or the probability that the matrix rating was randomly generated, was 0.02, and this indicates acceptable consistency (Saaty 1977).

## GIS-based suitability model and RWH suitability maps

A suitability model was developed using the model builder of ArcGIS 10.1. The model generates suitability maps for

**Table 4** | AHP pair-wise matrix for the factors used in this study. The CR, 0.02, thus the judgments made are acceptable (Saaty 1977)

| | Texture | Land cover | Slope | Rainfall surplus | Runoff |
|---|---|---|---|---|---|
| Texture | 1 | 6 | 5 | 3 | 1 |
| Land cover | 1/6 | 1 | 1/2 | 1/4 | 1/7 |
| Slope | 1/5 | 2 | 1 | 1/3 | 1/4 |
| Rainfall surplus | 1/3 | 4 | 3 | 1 | 1/2 |
| Runoff | 1 | 7 | 4 | 3 | 1 |

RWH by integrating different input factor maps using weighted overlay process, by utilizing both vector and raster databases. With a weighted linear combination, factors are combined by applying a weight to each, and the results are summed up to yield a suitability map using the WEIGHT module of IDRISI software (Table 5).

## RESULTS AND DISCUSSION

We generated a suitability map for RWH with four suitability classes – excellent, good, moderate, and poor and unsuitable (Figure 10). The sites shown in the map are those identified by DSS with either very high or high suitability levels for RWH. The excellent and good areas lie mainly in the southern and western parts of the study area. The central part is mostly good and moderately suitable with some excellent locations. The northern and eastern parts almost have the same categories, which are dominated by good, moderate, and poor and unsuitable areas, although some locations show excellent suitability. This is attributed to difference in spatial variability in parameters important for identifying PRWH technologies including soil, rainfall surplus, and slope, e.g., the southern and western parts of the study area being largely hilly and with more drainage networking compared to other locations, which is relatively flat or having very mild slopes and less drainage networking. The potential suitable sites for different types of RWH technologies as determined by the DSS for the study area are shown in Table 6. According to Table 6, 12.2 and 22.2% of the study area has excellent and good suitability for RWH, respectively, while 34.7% and 30.9% of the area exhibit moderate suitability and are poor and unsuitable, respectively.

**Table 5** | Weight (percentage of influence)

| No. | Factors | Weight | Weight % |
|---|---|---|---|
| 1 | Soil texture | 0.361 | 36.063 |
| 2 | Land cover/use | 0.047 | 4.683 |
| 3 | Slope | 0.077 | 7.676 |
| 4 | Rainfall surplus | 0.160 | 15.996 |
| 5 | Potential RC | 0.356 | 35.582 |
| | Sum | 1 | 100 |

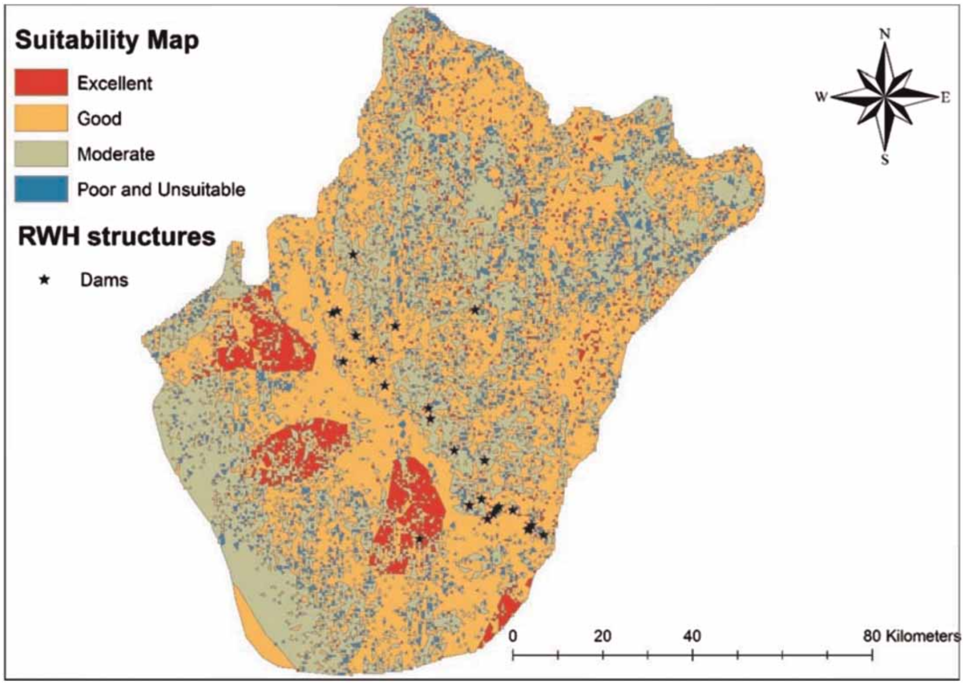

**Figure 10** | Map of PRWH techniques in Al-Baha region, Saudi Arabia.

**Table 6** | Percentage of potential sites for different types of RWH in Al-Baha region, Saudi Arabia as predicted by the DSS

| Suitability | Percent of total area |
|---|---|
| Excellent | 12.2 |
| Good | 22.2 |
| Moderate | 34.7 |
| Poor and unsuitable | 30.9 |

The PRWH technologies identified and shown in Figure 10 reflect specific suitability levels of factors and weight of factors. For example, most suitable sites for RWH are located in the higher rainfall areas with slopes ranging from moderately undulating to steep. These results agree with field observations, which indicated that most of the areas with excellent to good suitability have slopes between 2 and 8% and are intensively cultivated areas. The major soil types in the areas with excellent to good suitability are clay, clay loam, and loam, and the rainfall ranges from 150 to 200 mm. Moreover, the results agree with findings obtained by Mbilinyi *et al.* (2005).

Results of spatial distributions of modeled runoff showing a variation from as low as 0 to a maximum of 0.82 were observed due to divergence in topography and climate in the study area, where the largest rainfall was observed in the mountainous area. As noticed during the field survey, the mountainous areas are exposed to the formation of clouds and fog, and this often happens in winter due to air masses coming from the Red Sea. The mountainous area also has the largest runoff depth due to its soil type, land cover conditions, and the steep slope.

The large spatial variability in mean RC, which ranges from 0 to 0.82, is relatively well explained by mean annual precipitation. Runoff coefficients tend to increase with mean annual precipitation. The significance of this relationship means that mean annual precipitation influences the distribution of RCs not only through the characteristics of the flood-generating storm events, but also by controlling the variability of the initial conditions and, at longer time scales, likely by controlling the geomorphological structure of catchments, through soil formation and erosion processes.

Many researchers in different parts of the world have used runoff depth as an indication for mapping potential RWH sites for different purposes. De Winnaar *et al.* (2007) used runoff depth for identifying the potential RWH sites for the Thukela River Basin, South Africa. Ramakrishnan *et al.* (2008) used runoff potential as a factor to select suitable sites for various RWH/recharging structures in the Kali watershed, Dahod district of Gujarat of India, using RS and GIS techniques. Durga Rao & Bhaumik (2003) identified runoff potential as a factor to identify suitable sites for RWH. However, in Saudi Arabia no work has been done to date in this area.

In this study, it has been established successfully that RS and GIS can provide the appropriate platform for convergence of large volume of multi-disciplinary data. Many regions of Saudi Arabia as well as of developing countries do not have sufficient historical records and detailed runoff information needed for physically based distributed models. In these cases, this study can provide a better solution for flood management programs.

The described technique is economical and has high accuracy in determining the flood hydrograph for any area as it uses DEM of the area that can be freely accessed from SRTM or ASTER sources. This finding is in good agreement with Mahmoud *et al.* (2014c) and Mahmoud (2014b). Determination of RC is important for flood control channel construction and for possible flood zone hazard delineation. A high RC value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel.

The availability of RWH structures in the study area supported farmers with sufficient water for irrigation and agriculture development. This confirms and proves the relationship between water availability, agriculture development, and human activities which are the same reason for deforestation in the study area. These results agree with field observations, which indicated that most of the cultivated areas were close to RWH structures. Moreover, the results agree with findings obtained by Jackson *et al.* (2001) and Krishna (2003).

Another suitability model that is obtained when all the factors are assigned equal influence (Figure 11) shows that 5% and 34.4% of the study areas have excellent and good suitability, respectively, while 44.8% and 15.8% of the study area are moderate and poor and unsuitable, respectively.

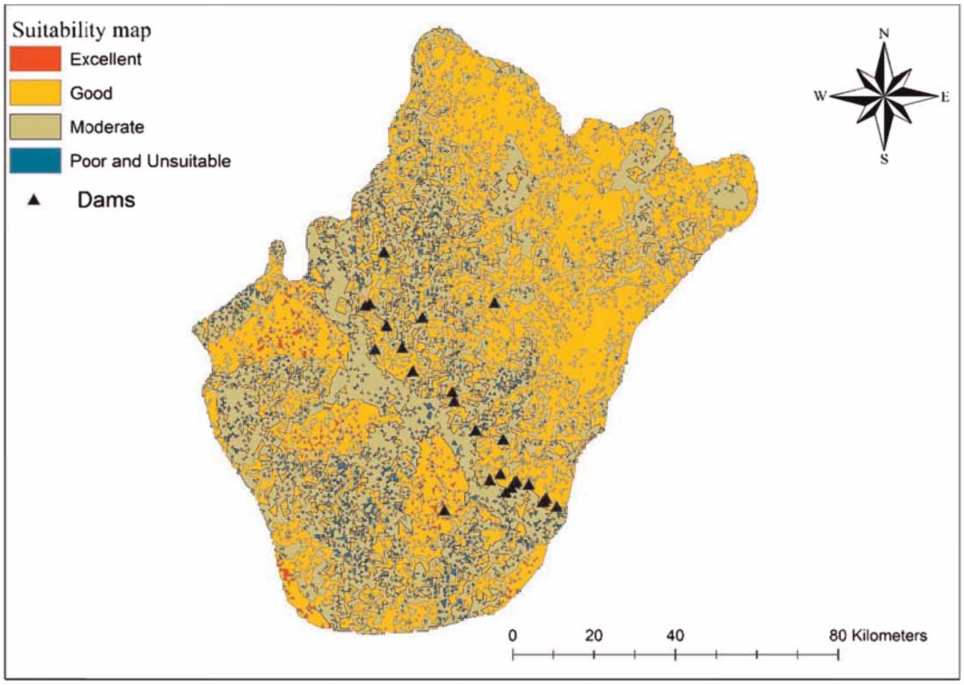

**Figure 11** | Map of PRWH techniques in Al-Baha region, Saudi Arabia using equal importance.

During the field survey, 25 dams were found within the study area. Here, 70% of the existing dams were established for RWH and groundwater recharge. This is justified because the groundwater resources were depleted in the area around the dams before their construction. Such depletion over the years hindered agricultural activities in the area since the main sources of water here are groundwater wells. Furthermore, it was revealed that only 4% of the dams are for irrigation purposes and other activities and 12% for flood control. In addition, 14% of the dams were established for supplying drinking water, in regions where desalinated water is somewhat difficult to obtain. The fact that the main purposes of most of the dams in the study area are groundwater recharge and RWH give an indication of the importance of this study.

The locations of the existing RWH dams were checked against the generated suitability map by using the proximity analysis tool ArcGIS 10.1. Most of the existing RWH structures that were categorized as successful were within the good areas (72% of the structures) followed by the moderately suitable areas (24% of the structures). Only 4% of the existing RWH structures lie in areas classified as excellent. A total of 76% of the successful existing RWH structures are located at sites that fall in the good and excellent areas. This validates the database and methodology used for developing the suitability model.

## CONCLUSIONS AND RECOMMENDATIONS

Identification of PRWH is an important step toward maximizing water availability and land productivity in arid and semi-arid regions. RWH can be used to provide water for agricultural use in arid regions where no surface water is available for human activities. This is especially important for Saudi Arabia where the water demands for agricultural as well as domestic purposes are met mainly by groundwater resources and where cost-intensive processes such as desalination are necessary. Against this background, RWH may prove to be an alternative and indispensable source of water.

This study presents a GIS methodology that is based on a DSS employing RS data, field survey data, and GIS to delineate potential RWH areas. Suitable locations were identified and the existing RWH structures in Al-Baha Province were evaluated using a suitability model. The suitability map generated classifies the region into four suitability classes – excellent, good, moderate, and poor and unsuitable. This map can be used to plan and set up RWH structures at the most suitable locations to ensure their successful application for providing water for agriculture.

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